An Automatic Finite-Sample Robustness Metric: Can Dropping a Little Data Make a Big Difference?

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Dropping data: Mexico Microcredit

Example: Angelucci et al. [2015], a randomized controlled trial study of the efficacy of microcredit in Mexico based on $N =$16,560 data points. A regression was run to estimate the average effect of microcredit.

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Cannot find influential subsets by brute force!

We provide a fast, automatic tool to approximately identify the most influential set of points.

Outline

- Why and when might you care about sensitivity to data dropping?
- How do we identify influential sets? When is our method accurate?

  (A formalization of the problem and the class of estimators we study.)
- Examine real-life examples of analyses: some sensitive, some not.

  (The results may defy your intuition.)
- What kinds of analyses are sensitive to data dropping?

  (Comparison to standard errors, gross errors, and how to mitigate.)

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    - Don't care about sensitivity to small subsets.

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Specifically, often in statistical applications:

- Policy population is different from analyzed population,
- Small fractions of data are missing not-at-random,
- We report a convenient summary (e.g. mean) of a complex effect.

Formalizing the question.

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$$\hat{\theta} := \underset{\theta}{\arg\min} \frac{1}{2} \sum_{n=1}^{N} \left(y_n - \theta^T x_n\right)^2$$

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Make a qualitative decision using:

- A particular component: $\hat{\theta}_k$
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Make a qualitative decision using $\phi(\hat{\theta})$ for a smooth, real-valued ϕ.

(WLOG try to increase $\phi(\hat{\theta})$.)

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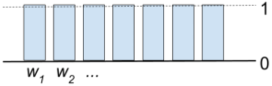
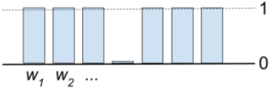
Original weights: $\vec{1} = (1, \ldots, 1)$



Leave points out by setting their elements of w to zero.



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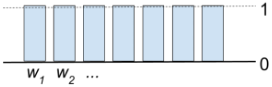

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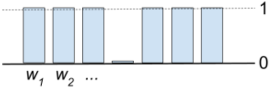
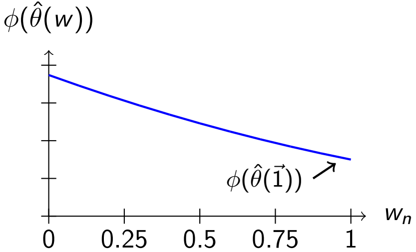


The map $w \mapsto \phi(\hat{\theta}(w))$ is well-defined even for continuous weights.

Taylor series approximation.



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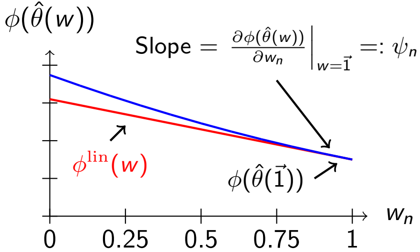

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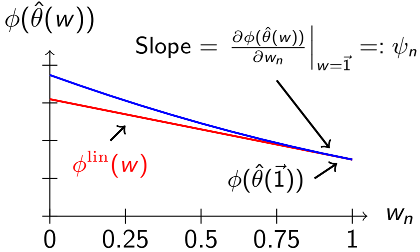

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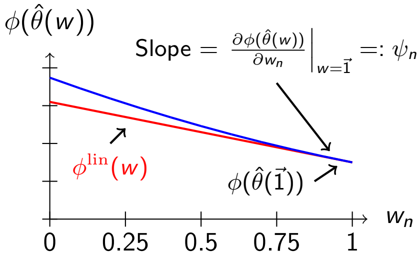

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We can use ψ_n to form a Taylor series approximation:

$$\phi(\hat\theta(w)) \approx \phi^{\mathrm{lin}}(w) := \phi(\hat\theta(\vec{1})) + \sum_{n=1}^{N} \psi_n (w_n - 1)$$

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Dropped points have $w_n - 1 = -1$. Kept points have $w_n - 1 = 0$
$\Rightarrow$ The most influential points for $\phi^{\mathrm{lin}}(w)$ have the most negative ψ_n.

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How to compute the ψ_n's? And how accurate is the approximation?

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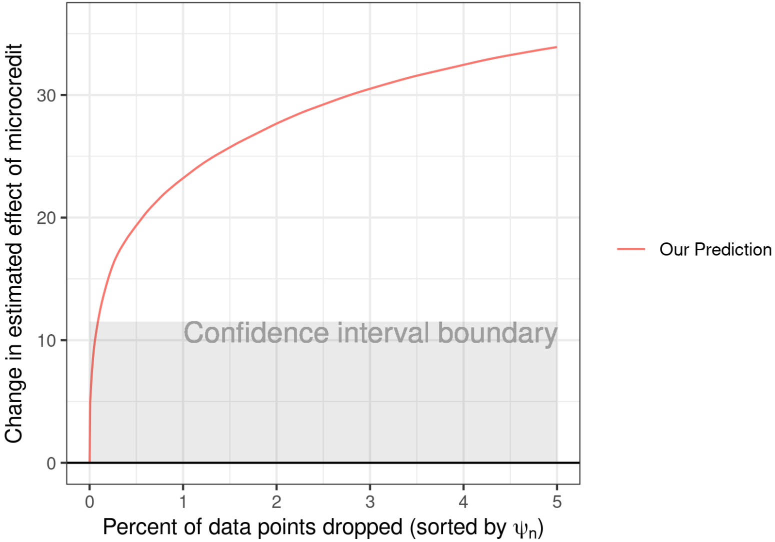
$\Rightarrow$ The ψ_n are automatically computable from $\hat{\theta}(\vec{1})$ and software implementations of $G(\cdot, \cdot)$ and $\phi(\cdot)$ using **automatic differentiation**.

```
> import jax
> import jax.numpy as np
> def phi(theta):
>     ... computations using np and theta ...
>     return value
>
> # Exact gradient of phi (first term in the chain rule above):
> jax.grad(phi)(theta_opt)
```

See `rgiordan/vittles` on `github`.

How accurate is the approximation?

Checking the approximation for Mexico microcredit.



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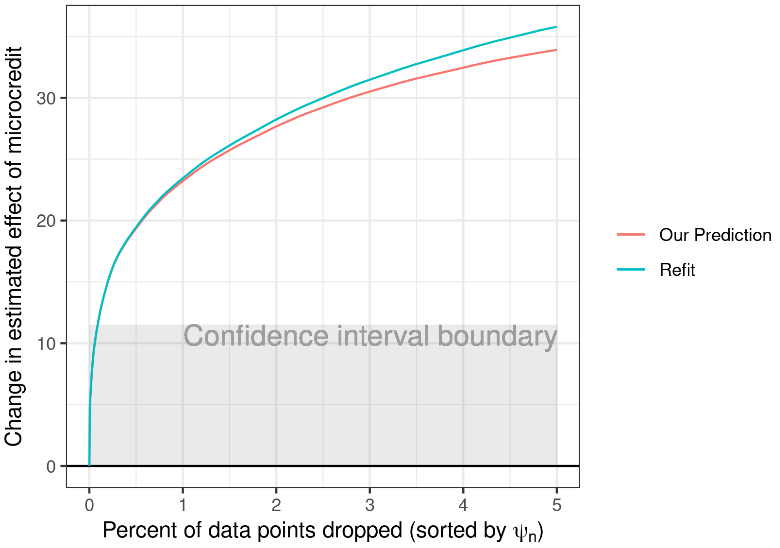

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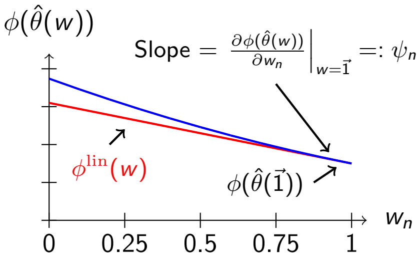

We provide **finite-sample theory** [Giordano et al., 2019b] showing that

$$\left|\phi(\hat{\theta}(w)) - \phi^{\mathrm{lin}}(w)\right| = O\left(\left\|\frac{1}{N}(w - \vec{1})\right\|_2^2\right) = O(\alpha) \text{ as } \alpha \to 0.$$

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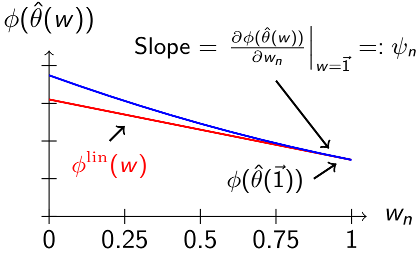

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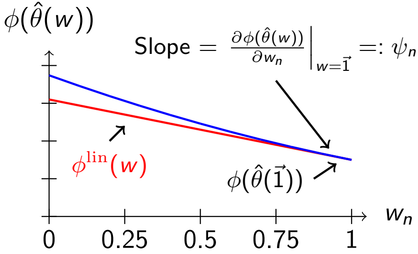

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But you don't need to rely on the theory to show non-robustness!

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(Let $\mathcal{W}_\alpha$ denote weight vectors dropping $\lfloor \alpha N \rfloor$ points, and $w^* := \mathrm{argsup}_{w \in \mathcal{W}_\alpha} \phi^{\mathrm{lin}}(w)$. Then $\phi(w^*) \le \sup_{w \in \mathcal{W}_\alpha} \phi(w)$.)

Selected experimental results.

Original estimate (SE)	Refit estimate (SE)	Observations dropped
-4.549 (5.879)	7.030 (2.549)*	$15 = 0.09\%$

Table: Microcredit Mexico results ($N = 16560$) [Angelucci et al., 2015].

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Table: Cash transfers results (N = 10518) [Angelucci and De Giorgi, 2009]

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0.029 (0.005)*	-0.009 (0.004)*	224 = 0.96%

Table: Medicaid profit results (N = 23361) [Finkelstein et al., 2012]

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What makes an analysis sensitive? Preliminaries

We are **robust to data dropping** if, for the Δ that changes conclusions and w^* dropping the $\lfloor \alpha N \rfloor$ most influential points,

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Contrast with sampling variability.

A 95% CI is given by $\phi(\hat{\theta}(\vec{1})) \pm \frac{1.96}{\sqrt{N}}\hat{\sigma}_\phi$. We reject $\phi(\hat{\theta}(\vec{1})) + \Delta$ when

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The **signal to noise ratio** $\frac{\Delta}{\hat\sigma_\phi}$ determines robustness to data dropping **and** sampling variability, but with **different thresholds**.

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$\Rightarrow$ A result can be made significant by a change of no more than $\frac{1.96}{\sqrt{N}} \hat{\sigma}_\phi$.

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- **P-hacking is dropping non-robust for large N.**
Proof: P-hacked effect sizes are of the order $\frac{1.96}{\sqrt{N}}\hat{\sigma}_\phi$.

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Dropping robustness should **augment** other forms of robustness.

How to make an analysis less sensitive?

Robust to data dropping:
("dropping robustness")

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To achieve dropping robustness, reduce $\hat{\sigma}_\phi$ and / or increase Δ.
Proof: Across typical distributions, $\hat{\mathscr{S}}_\alpha$ varies little. (Details in paper.)

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In the Mexico microcredit example,

$$\hat{\sigma}_\phi = 757.8 \qquad \phi(\hat{\theta}(\vec{1})) = -4.55 \qquad N = 16,560$$

The study overcame a very low signal to noise ratio with a very large N.

This (canonical) response to low signal to noise ratio — to gather more data — produces small SEs, but cannot produce dropping robustness.

Conclusion

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- We can quickly and automatically find an approximate influential set which is accurate for small sets.
- Data dropping robustness is principally determined by the signal to noise ratio, and captures sensitivity distinct from sampling and gross error sensitivity.

Links and references

Tamara Broderick, Ryan Giordano, Rachael Meager (alphabetical authors)
"An Automatic Finite-Sample Robustness Metric: Can Dropping a Little Data Change Conclusions?"
https://arxiv.org/abs/2011.14999

Select blog posts with more details: `https://rgiordan.github.io`

- Data dropping sensitivity overcomes p-hacking
- Collinearity in OLS after dropping
- Influence functions and sums
- Connections to the bootstrap

Related software on `github`:

- rgiordan/zaminfluence (for `R`)
- rgiordan/vittles (for `Python`)

Some of my work on other forms of robustness:

- Prior sensitivity in Bayesian nonparametrics [Giordano et al., 2021]
- Approximate cross-validation (and other reweightings) [Giordano et al., 2019b,a]
- Covariances and prior sensitivity for mean field VB [Giordano et al., 2015, 2018]
- Model sensitivity of MCMC output [Giordano et al., 2018]
- Frequentist variances of MCMC posteriors (in progress)

References

M. Angelucci and G. De Giorgi. Indirect effects of an aid program: How do cash transfers affect ineligibles' consumption? *American Economic Review*, 99(1):486–508, 2009.

M. Angelucci, D. Karlan, and J. Zinman. Microcredit impacts: Evidence from a randomized microcredit program placement experiment by Compartamos Banco. *American Economic Journal: Applied Economics*, 7(1):151–82, 2015.

P. Bickel, C. Klaassen, Y. Ritov, and J Wellner. *Efficient and adaptive estimation for semiparametric models*, volume 4. Johns Hopkins University Press Baltimore, 1993.

A. Finkelstein, S. Taubman, B. Wright, M. Bernstein, J. Gruber, J. Newhouse, H. Allen, K. Baicker, and Oregon Health Study Group. The Oregon health insurance experiment: Evidence from the first year. *The Quarterly Journal of Economics*, 127(3):1057–1106, 2012.

R. Giordano, T. Broderick, and M. I. Jordan. Linear response methods for accurate covariance estimates from mean field variational Bayes. *Advances in Neural Information Processing Systems*, 28:1441–1449, 2015.

R. Giordano, T. Broderick, and M. I. Jordan. Covariances, robustness and variational Bayes. *The Journal of Machine Learning Research*, 19(1):1981–2029, 2018.

R. Giordano, M. I. Jordan, and T. Broderick. A higher-order Swiss army infinitesimal jackknife. *arXiv preprint arXiv:1907.12116*, 2019a.

R. Giordano, W. Stephenson, R. Liu, M. I. Jordan, and T. Broderick. A Swiss army infinitesimal jackknife. In *The 22nd International Conference on Artificial Intelligence and Statistics*, pages 1139–1147. PMLR, 2019b.

R. Giordano, R. Liu, M. I. Jordan, and T. Broderick. Evaluating sensitivity to the stick-breaking prior in Bayesian nonparametrics. 2021.

F. Hampel. *Robust statistics: The approach based on influence functions*, volume 196. Wiley-Interscience, 1986.

P. Huber. *Robust Statistics*. John Wiley & Sons, New York, 1981.

R. Mises. On the asymptotic distribution of differentiable statistical functions. *The Annals of Mathematical Statistics*, 18(3):309–348, 1947.

J. Reeds. *On the definition of von Mises functionals*. PhD thesis, Statistics, Harvard University, 1976.

Extra slides

A simulation

For $N = 5,000$ data points, compute the OLS estimator from:

Regressors	Residuals	Responses
$x_n \sim \mathcal{N}(0, \sigma_x^2)$	$\varepsilon_n \sim \mathcal{N}(0, \sigma_\varepsilon^2)$	$y_n = 0.5 x_n + \varepsilon_n$

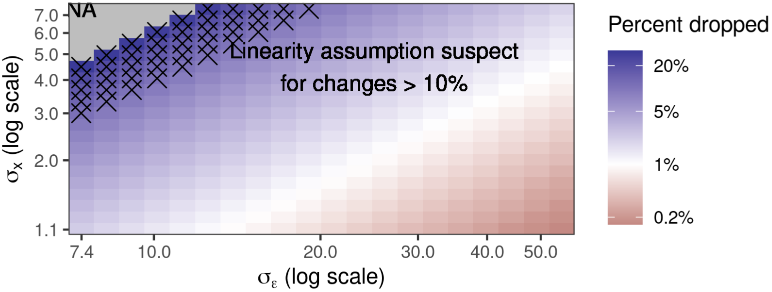

Figure: The approximate perturbation inducing proportion at differing values of σ_x and σ_ε. Red colors indicate datasets whose sign can is predicted to change when dropping less than 1% of datapoints. The grey areas indicate $\hat{\Psi}_\alpha = \mathtt{NA}$, a failure of the linear approximation to locate any way to change the sign.

Influence function

The present work is based on the *empirical influence function*. Consider:

- True, unknown distribution function $F_\infty(x) = p(X \le x)$
- Empirical distribution function $\hat{F}(x) = \frac{1}{N} \sum_{n=1}^{N} \mathbb{I}\left(x_n \le x\right)$
- A statistical functional $T(F)$.

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We estimate with $T(F_\infty)$ with $T(\hat{F})$.
Sample means are an example:

$$T(F) := \int x \, F(\mathrm{d}x).$$

Z-estimators are, too:

$$T(F) := \theta \text{ such that } \int G(\theta, x) F(\mathrm{d}x) = 0.$$

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Form an (infinite-dimensional) Taylor series expansion at some F_0:

$$T(F) = T(F_0) + T'(F_0)(F - F_0) + \mathrm{residual}.$$

When the derivative operator takes the form of an integral

$$T'(F_0)\Delta = \int \psi(x; F_0)\Delta(\mathrm{d}x)$$

then $\psi(x; F_0)$ is known as the *influence function*.
Where to form the expansion? There are at least two reasonable choices:

- The limiting influence function $\psi(x, F_\infty)$
- The empirical influence function $\psi(x, \hat{F})$

Influence function

- The limiting influence function (LIF) $\psi(x, F_\infty)$
  - Used in a lot of classical statistics [Mises, 1947, Huber, 1981, Hampel, 1986, Bickel et al., 1993]
  - Unobserved, asymptotic
  - Requires careful functional analysis [Reeds, 1976]
- The empirical influence function (EIF) $\psi(x, \hat{F})$
  - The basis of the present work (also [Giordano et al., 2019b,a])
  - Computable, finite-sample
  - Requires only finite-dimensional calculus

Typically the *semantics* of the EIF derive from study of the LIF.
Example: $\frac{1}{N}\sum_{n=1}^{N}(N\psi_n)^2 \approx \mathrm{Var}\left(\sqrt{N}\phi(\hat{\theta})\right)$.

But the EIF measures what happens when you perturb the data at hand.

Other data perturbations will admit an analysis similar to ours!

Local robustness

The present work is an application of *local robustness*. Consider:

- Model parameter λ (e.g., data weights $\lambda = w$)
- Set of plausible models $\mathcal{S}_\lambda$ (e.g. $\mathcal{S}_\lambda = W_\alpha$)
- Estimator $\hat{\theta}(x, \lambda)$ for data x and $\lambda \in \mathcal{S}_\lambda$ (e.g. a Z-estimator)

Global robustness: $\left(\inf_{\lambda \in \mathcal{S}_\lambda} \hat{\theta}(x, \lambda), \sup_{\lambda \in \mathcal{S}_\lambda} \hat{\theta}(x, \lambda)\right)$ (Hard in general!)

Local robustness: $\left(\inf_{\lambda \in \mathcal{S}_\lambda} \hat{\theta}^{lin}(x, \lambda), \sup_{\lambda \in \mathcal{S}_\lambda} \hat{\theta}^{lin}(x, \lambda)\right)$

...where $\hat{\theta}^{lin}(x, \lambda) := \hat{\theta}^{lin}(x, \lambda_0) + \left.\frac{\partial \hat{\theta}^{lin}(x, \lambda)}{\partial \lambda}\right|_{\lambda_0} (\lambda - \lambda_0)$.

Many variants are possible!

- Cross-validation [Giordano et al., 2019b]
- Prior sensitivity in Bayesian nonparametrics [Giordano et al., 2021]
- Model sensitivity of MCMC output [Giordano et al., 2018]
- Frequentist variances of MCMC posteriors (in progress)